STRUCTURAL LOADING STATISTICS OF LIVE GUN FIRINGS FOR THE ARMY'S EXCALIBUR PROJECTILE

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April 2005

ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Armaments Engineering & Technology Center

Picatinny, New Jersey

REPORT DOCUMENTATION PAGE

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From – To)
April 2005	Interim	Jan 2002 to Jan 2005

4. TITLE AND SUBTITLE

STRUCTURAL LOADING STATISTICS OF LIVE GUN FIRINGS FOR THE ARMY'S EXCALIBUR PROJECTILE

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHORS

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Fuze and Precision Armaments
Technology (AMSRD-AAR-AEP-E)
Picatinny. NJ 07806-5000

Raytheon Missile Systems
P.O. Box 11337, Bldg 802
Tucson, AZ 85734

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

ARDEC, EM
Technical Research Center (AMSRD-AAR-EMK)
Picatinny, NJ 07806-5000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

Technical Report ARAET-TR-05005

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Excalibur is a 155-mm projectile under development and scheduled for Army use in 2008. During development, Excalibur was gun-fired using a variety of propellant charges. The purpose of the tests was to determine the reliability, structural integrity, and performance for different field charges. On-board accelerations and gun-tube pressures were recorded for most tests. This paper summarizes the accelerations and pressures from dozens of tests using different propellant charges. Average pressures and accelerations are presented. Variations and correlations are also given.

15. SUBJECT TERMS

Accelerometers, Acceleration, Excalibur, Instrumentation, Guns, Dynamics, Projectile pressures, Statistical correlations, Balloting, Set-back, and Set-forward

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			J. A. Cordes
U	U	U	SAR	17	19b. TELEPHONE NUMBER (Include area code) (973) 724-6147

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INTRODUCTION

The Army's projectiles are routinely gun-fired during the development phase. The objectives of Excalibur's gun firing were: 1) validate the strength and operability of components, subsystems, and systems; 2) characterize the gun-launch loads for failure reviews; 3) identify weak subsystems for redesign; and 4) determine the range and accuracy for different propellant charges.

To characterize gun-launch loads other munitions were instrumented. Lee (ref. 1) was one of the first researchers to document the internal ballistics by instrumentation. In 1993, Lee published a paper describing seven live firings of a 155 mm with pressure transducers. Lodge and Dilkes (ref. 2) used accelerometers and displacement transducers to measure in-bore dynamics. Using a smooth-barrel, 120-mm gun, three projectiles were fired. Wilkerson and Palathingal (ref. 3) reported on an instrumented 120-mm M832E1 heat round. David, Brown, Myers, and Hollis (ref. 4) described some of the commercially available equipment for measuring accelerations in different directions. Katulka, Pergino, Muller, McMullen, Wert, and Ridgley (ref. 5) recorded both axial acceleration and pressures on a 120-mm projectile. They used telemetry to transmit data. Presented in the referenced paper was one resulting pressure and acceleration curve. While the acceleration curve had a different signature than Excalibur, some of the local time variations were similar to the Excalibur curves. Szymanski (ref. 6) designed and assembled an instrumentation package for a 4-in. air gun with strain gages and accelerometers.

This paper reports the extensive effort to characterize the gun-tube pressures and the accelerations for Excalibur. Excalibur's live-fire test program uniquely incorporates both pressure sensors and three-axis accelerometers, spans a range of charges, and includes multiple firings at various charges.

METHOD: LIVE FIRE TESTS

Figure 1 shows a sketch of the gun tube and projectile. The pressure sensor locations are shown as P1 through P7. Sensor P1 measures the breech pressure. Sensor P2 is close to the base at shot start and provides a reasonable estimate of base pressure, particularly for the first centimeters of motion. The accelerometers are located in the projectile in the on-board-recorder (OBR).

M284 GUN TUBE

PRESSURE SENSOR LOCATION

Dimensions in meters
Sketch, not to scale
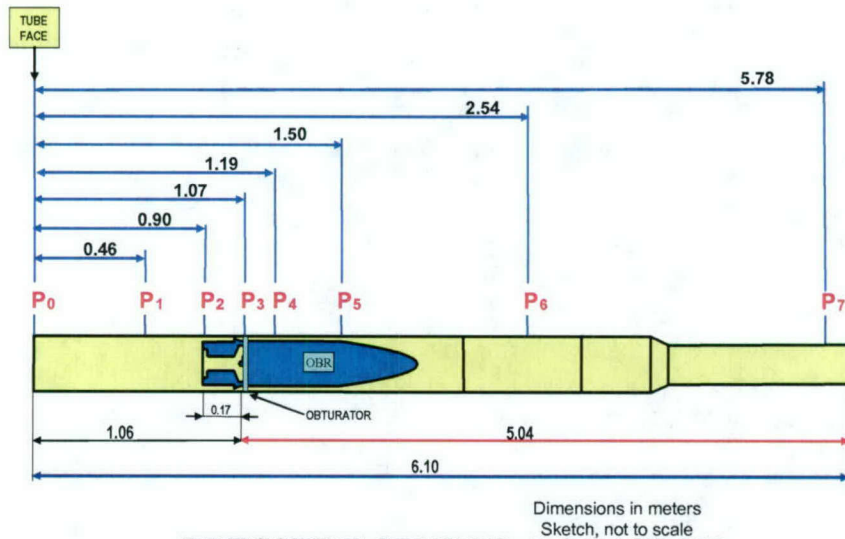
Figure 1
Gun tube, projectile, and pressure sensor locations

For live-fire shots, the projectile shown in figure 1 is a soft-recovery vehicle. The soft-recovery vehicle was modeled after the tactical Excalibur, but instead of a regular payload, the payload section contains a parachute. The vehicle is about 1-m long and has a mass of about 50 kg. The vehicle was designed to deploy the parachute and land softly without additional damage to sensitive electronic components. For most firings, the soft-recovery vehicle has a base, control section, and forward nose similar to the Excalibur. An OBR is located about 0.5 m from the base of the projectile. In the OBR section, three perpendicular accelerometers measure accelerations in the axial and two transverse (balloting) directions. The sample rate is recorded at approximately 500,000 samples per second with an anti-alias filter of 50 kHz. Accelerations are measured through the in-bore gun firing and muzzle exit events. Following landing, the soft recovery vehicle is taken apart and the structural integrity of parts is evaluated. If failures have occurred, the recorded pressures and accelerations are compared to other data sets as part of the root cause investigation.

RESULTS

Single Shot Acceleration Example

Figure 2 shows recorded accelerations for one of the margin shots. A margin shot uses a charge (e.g., an Army's PIMP+5% charge), which is greater than an operational shot. Transverse accelerations were recorded in perpendicular directions that rotated with the projectile. One of the transverse accelerations is shown. The axial acceleration is relatively smooth near the maximum acceleration or 'set-back' region, occurring at about 0.035 sec for the OBR3 case.

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Muzzle exit occurs at about 0.011 sec. At muzzle exit, high frequency ± accelerations occur in the transverse and axial directions. The 'set-forward' acceleration corresponds to the minimum (-) axial acceleration and occurs at muzzle exit. The balloting acceleration is the maximum (+) transverse acceleration and occurs at muzzle exit. For the case OBR3 in figure 2, the set-back acceleration was +13299 G's, the set-forward acceleration was -3884 G's, and the maximum balloting acceleration was +2298 G's.
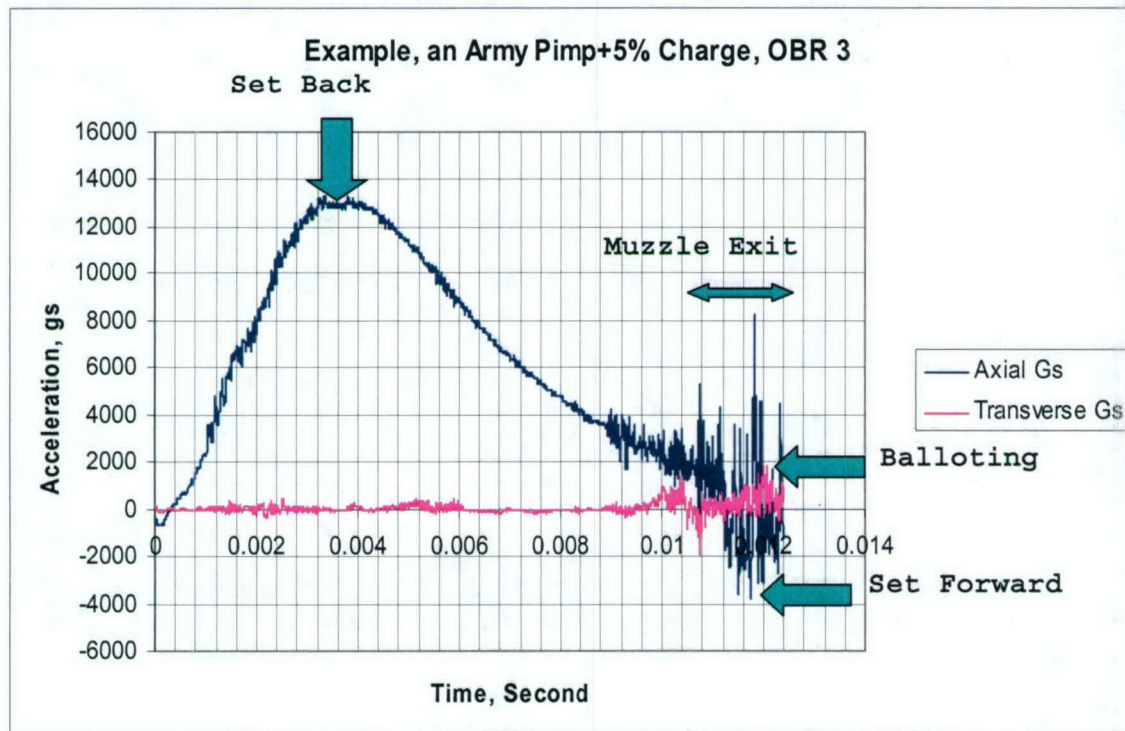
Figure 2
Example acceleration for an Army PIMP+5% charge, recorded

Projectile design requires consideration of both static and dynamic loads. Actual dynamic loads, such as the recorded accelerations shown in figure 2, are used for dynamic analysis. For dynamic analysis, frequency content and the change in magnitude of accelerations at muzzle exit are important considerations. A discussion of frequency content for gun firings is provided by Cordes and others (ref. 7). Just prior to muzzle exit, the base of the projectile passes the bore evacuator of the gun. The bore evacuator may also contribute to the magnitude and frequency content in the muzzle exit accelerations (ref. 8). In figure 2, the base of the projector passes the bore evacuator at about 0.009 sec.

Range of Charges

The Excalibur program includes test firings for a range of propellant charges. Table 1 shows the breech pressures for the live-firings. The coefficient of variation for breech pressure was 0.05 or less, indicating relatively small variations in measured breech pressure from shot to shot.

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Table 1
Summary of Excalibur live fire breech pressures

	Live firings: Excalibur pressures for live firings			
Charge zones	Number of firings	Average breech pressure (MPa)	Standard deviation	Coefficient of variation
PIMP +5%	10	385	17.5	0.05
Swedish 9++	3	385	8.6	0.02
PIMP	1	363		
MACS5	6	351	16.8	0.05
S8S	7	323	4.9	0.02
MACS4	4	117	2.6	0.02
7W	2	158	4.1	0.03
MACS2	1	137		
Charge 9 77B	5	275	3.0	0.01
MACS3	6	116	2.4	0.02

Preliminary design generally considers two static load cases. Both cases include an axial and a transverse acceleration. The transverse acceleration can be from any direction. The design cases are:

- Set-back with the maximum axial acceleration (+) and a relatively small transverse load (±)

- Muzzle exit with the minimum axial acceleration (-) and the maximum transverse acceleration (±). Muzzle exit is composed of ± accelerations, which may induce rattling and impacts within the sub-systems. These local impacts may cause high frequency shocks, which will adversely affect the sensitive electronic components.

Tables 2 through 6 show the average accelerations, the standard deviations, and the coefficients of variation for the set-back and muzzle exit accelerations. From tables 2 through 6 and the Excalibur tests, the following observations can be made:

- The maximum axial accelerations (+), like the measured breech pressures, have relatively small variations for the same charges

- The transverse acceleration at set-back is smaller than the transverse acceleration at muzzle exit. This was true for all shots. The transverse acceleration at set-back ranged between about 10% and about 50% of the muzzle exit acceleration.

- At muzzle exit, the measured set-forward (-) acceleration has a larger variation than the transverse acceleration

Table 2
Statistics on 10 PIMP+5% shots

PIMP+5% 10 shots	Set back		Muzzle exit	
	Maximum axial acceleration (Gs)	Transverse acceleration (Gs)	Minimum axial acceleration (Gs)	Maximum transverse acceleration (Gs)
Average	+15128	±340	-3919	±3743
Standard deviation	1279	411	1850	1213
Coefficient of variation	0.08	1.21	-0.47	0.32

Table 3
Statistics on three Swedish 9++ shots

9++ 3 shots	Set back		Muzzle exit	
	Maximum axial acceleration (Gs)	Transverse acceleration (Gs)	Minimum axial acceleration (Gs)	Maximum transverse acceleration (Gs)
Average	+17675	±2958	-2817	±6074
Standard deviation	1112	2755	518	162
Coefficient of variation	0.06	0.93	-0.18	0.03

Table 4
Statistics on 10 MACS5 shots

MACS5 10 shots	Set Back		Muzzle Exit	
	Maximum axial acceleration (Gs)	Transverse acceleration (Gs)	Minimum axial acceleration (Gs)	Maximum transverse acceleration (Gs)
Average	+15413	±609	-4869	±5001
Standard deviation	2050	946	2341	1783
Coefficient of variation	0.13	1.56	-0.48	0.36

Table 5
Statistics on seven 8S shots

8S 7 shots	Set back		Muzzle exit	
	Maximum axial acceleration (Gs)	Transverse acceleration (Gs)	Minimum axial acceleration (Gs)	Maximum transverse acceleration (Gs)
Average	+12656	±118	-3596	±3087
Standard deviation	948	63	778	803
Coefficient of variation	0.07	0.54	-0.22	0.26

Table 6
Statistics on four MACS3 shots

MACS3 4 shots	Set back		Muzzle exit	
	Maximum axial acceleration (Gs)	Transverse acceleration (Gs)	Minimum axial acceleration (Gs)	Maximum transverse acceleration (Gs)
average	+4165	±46	-70	±346
Standard deviation	364	41	191	115
Coefficient of variation	0.09	0.89	-2.72	0.33

Several correlations were completed for the live firings. Figure 3 shows the measured breech pressure and the maximum recorded accelerations, set back, in the axial direction. Figure 4 shows the relationship between measured pressure near the base and the maximum axial acceleration. The calculated maximum acceleration using $\vec{f} = m\vec{a}$ for a 48.9 kg 155-mm diameter projectile is also shown in figures 3 and 4. The straight line shows a linear trend line for the experimental data and the measure of correlation to the trend-line (R^2). The closer R^2 is to 1.0, the better the correlation between the two variables. The correlation of base pressure to maximum acceleration is better than the correlation with breech pressure.
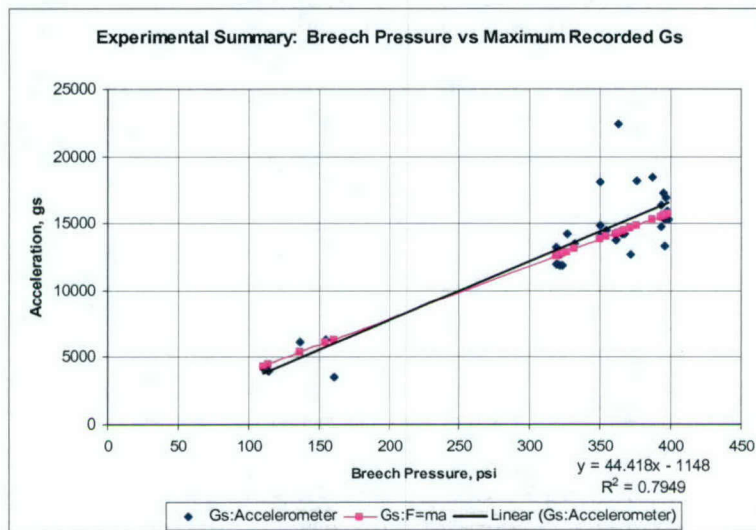
Figure 3
Correlation between <u>breech</u> pressures and maximum acceleration
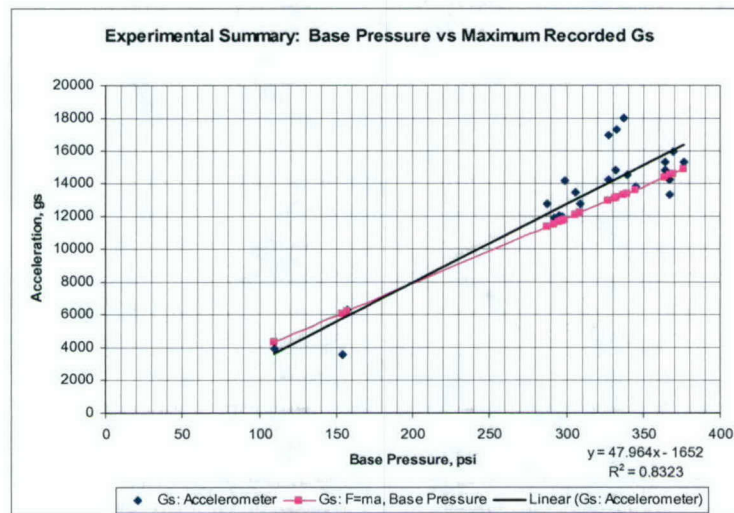

Figure 4
Correlation between <u>base</u> pressures and maximum acceleration

The set-forward and balloting accelerations were plotted against the maximum axial acceleration determine the relationship between set back and muzzle exit. Figure 5 shows the set-forward acceleration and figure 6 shows the maximum balloting acceleration as a function of the maximum acceleration. In both figures, the R^2 correlation is 50% or lower indicating a relatively large amount of data scatter and a relatively poor correlation to axial acceleration. The scatter in the balloting accelerations is less than scatter in the set-forward accelerations.
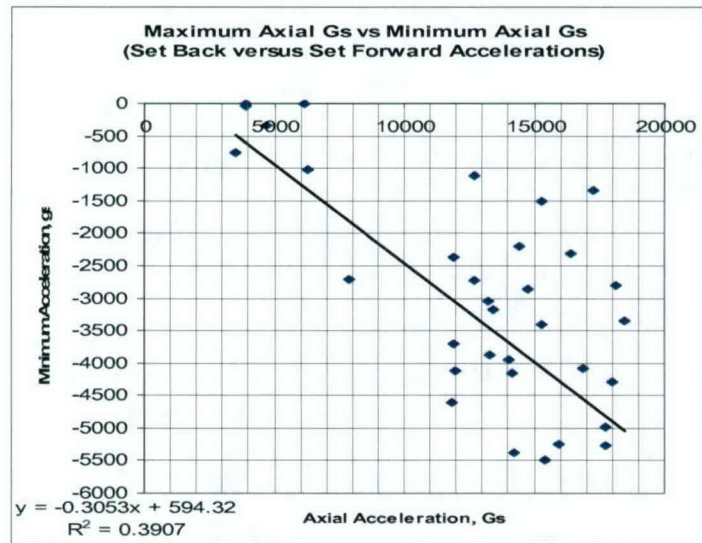
Figure 5
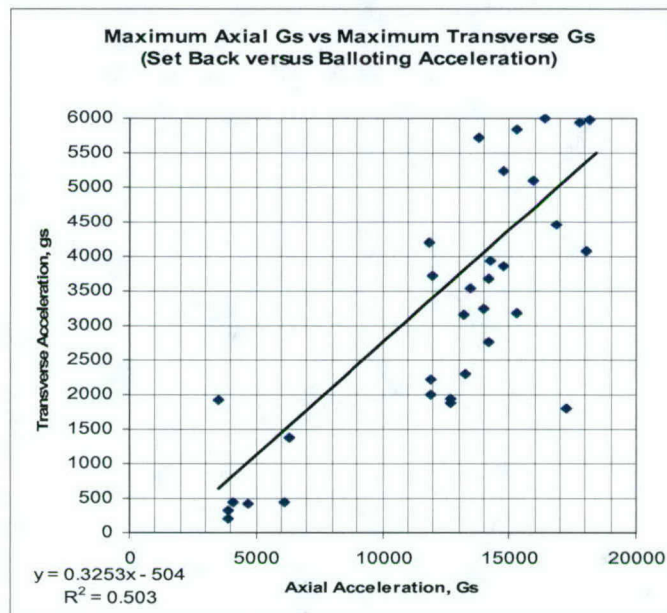Correlation maximum and minimum axial accelerations

Figure 6
Correlation between maximum axial and maximum transverse accelerations

DISCUSSION: MUZZLE EXIT VARIATIONS

Efforts are underway to understand the relatively large variations in the muzzle exit accelerations. In the simplistic sense, set-forward accelerations are dependent on the base pressure at muzzle exit. This base pressure causes a compression in the projectile. At muzzle exit, this base pressure decompresses within a very short time (~.1 to .5 ms). The dynamic decompression allows the projectile to spring back, thus creating a set-forward acceleration. This might lead one to believe that the set-forward can be related to base pressure at muzzle exit. The data does not support this simplistic approach. Future work will probably include correlating the P7 pressure (fig. 1) to the muzzle exit accelerations.

Muzzle exit is a very complicated event. As the nose of the projectile exits the barrel, the detached shock wave that was in the barrel, reattaches to the projectile nose causing vibrations to occur. In the barrel, the obturator and bourrletts support the projectile in the transverse direction and help to limit the transverse accelerations. When the forward bourrlett leaves the barrel, the projectile looses lateral support. This loss of lateral support allows for more transverse motion. Also, un-symmetric blow-by pressures caused by imperfect obturator sealing, have a magnified effect on the round due to the loss of the forward bourlett support. As the round exits the barrel, the support moment arm decreases (end of tube to aft bourrlett) and any moment unbalance that causes a round to barrel end impact creates a large reaction force. This large reaction force increases the transverse accelerations. The transverse accelerations couple into the axial accelerations. Thus, the large transverse accelerations at muzzle exit also result in large axial accelerations (±).

At muzzle exit, the transverse accelerations and axial accelerations may depend on additional factors. These factors include barrel wear, barrel straightness, blow-by pressures, bourlett clearance, charge, elevation, round and barrel differential temperatures, round alignment, and clocking (due to round center of gravity offsets) to name few. The scatter in the muzzle exit data is tied to the variations that affect muzzle exit behavior. This is in direct contrast to the F=ma equation which controls the quasi-static, set-back acceleration in which a very limited number of factors are present (mainly charge level). Future work should help identify which variables contribute most to the muzzle exit variations.

CONCLUSIONS

Based on the test results and the statistics, the following conclusions were reached:

- Variations in breech pressures between like charges are relatively small, having a coefficient of variation of 0.05 or less.

- Variations in the base pressures between like charges are slightly higher than the variations in the breech pressure.

- Variations in the maximum axial set-back accelerations between like charges are also relatively small, having a coefficient of variation of 0.08 or less.

- There is relatively good correlation between the pressure measured near the base of the projectile and the maximum acceleration at set-back.

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- The set-forward (-) and balloting accelerations have relatively high coefficients of variation and exhibit poor correlation to maximum axial acceleration or maximum pressure.

RECOMMENDATIONS

Set-forward (-) and balloting (±) accelerations exhibit relatively high variations. These variations should be considered in the design process. Set-forward and balloting loads (accelerations) should probably be determined by testing rather than scaling. Alternately, the averages, standard deviations, and the 99% confidence level values would include the variations in the set-forward and balloting loads and could be used for design.

The set-back accelerations and the pressures have relatively small variations from shot to shot. In most cases, these design values can be scaled or determined analytically.

REFERENCES

1. Lee, R., "Instrumented Projectile Firings in a 155-mm Regenerative Liquid Propellant Gun (RLPG) System", Report Number ARFSD-TR-93039, Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, Fire Support Armament Center, ADB177784 DTIC Public STINET http://stinet.dtic.mil, November, 1993.

2. Lodge, D.W. and Dilkes, A.M., "Use of an Instrumented 120MM Projectile for Obtaining In-Bore Gun Dynamics Data", Defense Evaluation and Research Agency Surrey (United Kingdom), ADP012483 DTIC Public STINET http://stinet.dtic.mil, April, 2001.

3. Wilkerson, S.A. and Palathingal, M., "Analysis of an Instrumented Projectile", Report ARL-MR-383, Army Research Lab Aberdeen Proving Ground MD, AD Number: ADA335770 DTIC Public STINET http://stinet.dtic.mil, December, 1997.

4. David, B. S.; Brown, T. G.; Myers, C. R.; and Hollis, M. S., "Ground and Flight Testing of Microelectromechanical Systems Sensors for the Commercial Technology Insertion Program", Army Research Lab, Attn: AMSRL-WM-PA, Aberdeen Proving Ground, MD 21005-5066, ADB233726 DTIC Public STINET http://stinet.dtic.mil, Sep, 1997.

5. Katulka, G. L.; Peregino, P. J.; Muller, P. C.; McMullen, K.; and Wert, R., "In-Bore Ballistic Measurements with Wireless Telemetry in Kinetic Energy Electro-Thermal-Chemical Projectiles", Director, U.S. Army Research Lab., Attn: AMSRL-WM-BA, Aberdeen Proving Ground, MD 21005-5066, ADB293505 DTIC Public STINET, September 2003.

6. Szymanski, E.A., "Acquiring Data for the Development of a Finite Element Model of an Airgun Launch Environment", U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, ADA422483 DTIC Public STINET, 19 May 2004.

7. Cordes, J. A.; Carlucci, D.; and Jafar, R., "Dynamics of a Simplified 155-mm Projectile", 21st International Symposium on Ballistics, 19 – 23 April 2004, Adelaide, South Australia, 1164-1170.

8. Carlucci, D.; Vega, J.; and Cordes, J.A., "Effect of a Bore Evacuator on Projectile In-Bore Dynamics", ARAET-TR-04017, November 2004, AD Number: ADA428620, DTIC Public STINET.

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